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Volume 1 of 3 Volumes

Assessment of Methane-Related Fuels for Automotive Fleet Vehicles

Executive Summary

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February 1982

Prepared for:
U.S. Department of Energy
Assistant Secretary for Conservation and Renewable Energy
Office of Vehicle and Engine R & D
Under Contract No. DE-AC01-80CS50179

Alternative Fuels Utilization Program

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Prepared by:
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Under Contract No. DE-AC01-80CS50179

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Alternative Fuels Utilization Program

II

FOREWORD

This report, prepared by The Aerospace Corporation for the Office of Vehicle and Engine R&D of the Department of Energy, provides an assessment of issues related to the supply and use of methane-related fuels in automotive spark-ignition and diesel engines. The term methane, as used in this report, includes and is interchangeable with natural gas as well as synthetic (or substitute) natural gas derived from coal, biomass, waste products or other renewable resources, provided methane is the predominant constituent. Methanol was included in this study because it is a liquid fuel producible from either natural gas or the same resources as synthetic natural gas. The assessment is based primarily on a comprehensive review of the open literature, supplemented by discussions with manufacturers and users of automotive natural gas systems and related equipment.

The report is divided into three volumes. This volume, Volume I, Executive Summary, provides summaries of results for all technical, supply, and economic assessments, and identifies research needed for the expanded use of natural gas in the automotive sector.

Volume II, Technical, Supply, and Economic Assessments, provides documentation of all study efforts and results. The areas addressed include vehicle fuel system and fueling station technology; vehicle performance, fuel economy, and emissions; resource energy utilization efficiency; potential petroleum displacement by alternative-fueled fleets; fuel supply; vehicle safety; user economics; and research needs.

Volume III, Appendices, provides data and evaluations in several technical areas which supplement Volume II assessments. Also included are the comments submitted by two organizations after their review of the draft report.

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ABSTRACT

This report assesses the use of methane-related fuels, derived from a variety of sources, in highway vehicles. The term methane, as used in this report, includes and is interchangeable with natural gas (NG) as well as synthetic (or substitute) natural gas (SNG), provided methane is the predominant constituent. Methanol is included in this study because it can be produced from NG or the same resources as SNG, and because it is a liquid fuel at normal ambient conditions. Technological, operational, efficiency, petroleum displacement, supply, safety, and economic issues are analyzed. The assessment is intended to satisfy Section 7(a) of the Methane Transportation Research, Development, and Demonstration Act of 1980 (PL 96-512), which focuses on expanded methane use in automotive fleet vehicles and farm equipment. Evaluations of institutional barriers and other alternative fuels were not included in this contract.

About 275,000 Italian and 20,000 domestic vehicles presently use NG. Conversion kits are commercially available for spark-ignition engines, but not for diesel vehicles. A typical dual-fuel (NG or gasoline) light-duty vehicle conversion costs $1250 to $2050, adds 175 to 300 pounds to vehicle weight, and adds to the gasoline driving range a range of 60 to 120 miles on compressed natural gas (CNG), or 200 to 400 miles on cryogenic liquefied natural gas (LNG). Both CNG and LNG require special fueling facilities and vehicle tanks. Methanol conversions are commercially available for $1500 to $2200. They do not significantly affect vehicle weight, but diminish driving range by 35 to 50 percent unless tank size is increased. For the most part, methanol fueling facilities and fuel systems are similar to those for gasoline, except for the use of different materials.

In principle, both NG and methanol allow more efficient engine operation than gasoline. In practice, engines are at present rarely optimized for NG and methanol. On the basis of energy expended from resource extraction to end use, only optimized LNG vehicles are more

efficient than their gasoline counterparts. By 1985, up to 16 percent of total United States petroleum-based highway vehicle fuel could be displaced by large fleets with central NG fueling depots. Excluding diesel vehicles, which need technology advances to use NG, savings of 8 percent are projected. Methanol use by large fleets could displace up to 8 percent of petroleum-based highway vehicle fuel from spark-ignition vehicles and another 9 percent from diesel vehicles, with technology advances.

United States NG supply appears adequate to accommodate fleet use. Supply projections, future price differential versus gasoline, and user economics are uncertain. In many cases, attractive paybacks can occur. CNG now costs on average about $0.65 less than gasoline, per energy-equivalent gallon. Methanol supply projections, future prices, and user economics are even more uncertain. Current and projected near-term methanol supplies are far from adequate to support fleet use. Methanol presently costs more than gasoline on an equal-energy basis, but is projected to cost less if produced from coal instead of NG or petroleum.

ACKNOWLEDGMENTS

Appreciation is acknowledged for the guidance and assistance provided by Dr. Ralph D. Fleming of the Department of Energy, Office of Vehicle and Engine R&D, who served as Project Manager for this study. Appreciation is also extended to many individuals and organizations who provided reference material and reviewed the draft of the report. In particular, the cooperation of Dual Fuel Systems, Inc., the Gas Service Energy Corporation, and the Environmental Protection Agency, who participated in the vehicle test program, is gratefully acknowledged.

During the course of this effort, industry involvement was solicited at all stages, from the study definition workshop in August 1980, through three bimonthly review meetings, and in two successive reviews of draft material. The cooperation of the following organizations in that process is gratefully acknowledged: American Gas Association; Argonne National Laboratory; Beech Aircraft Corporation; CNG Services, Inc.; Dual Fuel Systems, Inc.; Escher:Foster Technology Associates, Inc.; Ford Motor Company; Gas Service Energy Corporation; General Motors Corporation; Institute of Gas Technology; LNG Services, Inc.; Mueller Associates, Inc.; NCF Industries; New York State Energy Office; United States Environmental Protection Agency; and United States General Services Administration. Many constructive comments and suggestions were received from the reviewers, and these are incorporated in this report. In addition, appreciation is extended to the current users and developers of natural gas and methanol equipment who cooperated in providing data for this study.

The report is based on work performed by J. E. Clark, R. R. Covey, J. J. Donnelly, Jr., A. S. Levine, D. L. Levine, M. K. Martin, W. U. Roessler, and H. M. White.

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HIGHLIGHTS

This report assesses the potential for use of methane-related fuels in highway vehicles. Natural gas (NG), synthetic (or substitute) natural gas (SNG), and methanol derived from NG, coal, wood, and solid waste are considered. Methanol is included because it can be derived from NG or the same resources as SNG, and because it is a liquid fuel at normal ambient conditions. Topics covered include fuel system technology, vehicle operation, resource energy utilization, potential petroleum displacement, fuel supply, vehicle safety, user economics, and research needs. The assessment is intended to satisfy the requirements of Section 7(a) of the Methane Transportation Research, Development, and Demonstration Act of 1980 (PL 96-512), which focuses on expanded methane use in automotive fleet vehicles and farm equipment. Evaluations of institutional barriers, other alternative fuels, and alternative petroleum displacement options were not included in this study contract.

FUEL SYSTEM TECHNOLOGY

- Compressed natural gas (CNG) presently fuels approximately 275,000 private and fleet vehicles in Italy and about 20,000 fleet vehicles in the United States. Several thousand vehicles in France, Canada, Iran, and other countries also use CNG, and New Zealand plans to convert 150,000 vehicles to NG use by 1985. Liquefied natural gas (LNG) is used in about 200 fleet vehicles in the United States. Methanol is widely used in race cars, and over 100 methanol fleet vehicles are presently being evaluated in California.

- Conversion kits allowing dual-fuel operation with either CNG or gasoline are commercially available from a number of companies for spark-ignition (SI) engines. Conversion kits for LNG are also commercially available. No NG conversion kits are marketed for diesel vehicles.

- Conversion of a light-duty vehicle to dual-fuel CNG operation typically costs $1250 to $1850, adds almost 300 pounds to vehicle weight, and adds a CNG driving range of 60 to 120 miles to the gasoline range. System weight can be reduced by 30 to 40 percent using composite materials for the tanks. The tanks are usually mounted in the car's trunk or the truck's bed.

- Conversion of a light-duty vehicle to dual-fuel LNG operation typically costs $1650 to $2050, adds about 175 pounds to vehicle weight, and provides an LNG driving range of 200 to 400 miles. For single-fuel conversions, the net weight effect is less because the gasoline system can be removed. A trunk-mounted tank is usually used for cars. As with CNG, significant tank weight reductions are achievable with improved materials and designs.

- Fueling stations for CNG require a high-pressure compressor and high-capacity storage tanks. The tanks are unnecessary if overnight fueling is acceptable. A typical station servicing about 100 vehicles costs $60,000 to $100,000, excluding land and offsite utility tie-ins. Fueling stations for LNG require a cryogenic bulk storage tank and related equipment at a cost of approximately $110,000 for a 10,000 gallon installation.

- Single-fuel methanol conversions are commercially available for $1500 to $2200. Conversion to methanol adds relatively little to vehicle weight, but driving range is reduced by 35 to 50 percent unless tank size is increased. Methanol can be dispensed from existing gasoline stations if appropriate materials are used for the fuel handling equipment.

VEHICLE OPERATION

- NG has a very high octane rating and other favorable characteristics for automotive SI-engine applications. An SI engine fully optimized for NG operation is more efficient than its gasoline counterpart, given present gasoline octane levels. However, engine power tends to decrease because the gas displaces intake air. The loss can be partially recovered by spark timing optimization, and, in LNG systems, potentially by cooling the inducted air.

- The cetane rating of NG is extremely low, and it is unsuitable as a fuel for unmodified conventional diesel engines. Ignition aids, such as spark plugs, glow plugs, and supplemental injection of diesel fuel, are under investigation. In principle, conversion to NG should not greatly affect engine efficiency or power and should lessen smoke emissions, while increasing hydrocarbon and carbon monoxide emissions.

- Tests of experimental and fleet vehicles converted to NG operation are inconclusive regarding energy efficiency benefits. Both increases and decreases in efficiency have been experienced. Full-load engine power generally decreased significantly. Pollutant emissions were generally reduced, except for emissions of environmentally benign methane in some cases. The vehicles were primarily dual-fuel designs not optimized for NG

operation. Controlled tests of similar non-optimized vehicles conducted during this study showed only a 1 percent efficiency improvement, while power declined by 27 percent. Conversely, with an optimized design, energy efficiency gains of 20 percent or more are projected.

- Methanol also has a high octane rating which can be exploited. In principle, engine power tends to increase slightly with methanol, and emissions of all species except aldehydes tend to be lower. Like NG, methanol has a low cetane rating and cannot be directly used in unmodified conventional diesel engines. Limited tests of methanol vehicles show energy efficiency increases of 20 percent or more. However, since methanol has a lower heating value than gasoline, the fuel economy on a per-gallon basis is 35 to 50 percent lower.

RESOURCE ENERGY UTILIZATION

- Significant energy is expended in the fuel logistic chain from resource extraction to vehicle fueling. Only CNG produced from conventional NG has a logistic chain efficiency comparable to that of gasoline or diesel fuel. Production of methanol from coal is about as efficient as production of CNG from coal, and slightly less efficient than production of methanol from NG.

- Based on NG as the resource, only single-fuel LNG vehicles with SI engines are projected to consume less total resource energy than their gasoline counterparts. All other resources and fuel types result in higher consumption of resource energy. For diesels, if conversions became available, all except large trucks would have significantly higher resource energy consumption.

POTENTIAL PETROLEUM DISPLACEMENT

- Conversion of all fleets of 10 or more cars, or 6 or more trucks, to NG could potentially displace 17 billion gallons per year (GPY) of petroleum-based fuel by 1985, 16 percent of the projected highway vehicle total. Excluding diesels, for which technology advances would be required, the savings could be about 8 billion GPY or 8 percent of the total.

- If sufficient methanol became available, it could potentially displace 8 billion GPY of gasoline by 1985 from fleets of 10 or more cars or 6 or more trucks. Another 9 billion GPY of diesel fuel could also be displaced with technology advances. These are about 8 and 9 percent, respectively, of the projected highway vehicle total. However, the corresponding methanol production requirement far exceeds the projected supply.

FUEL SUPPLY

- Future gas supply depends on government policies, technological advancements, and economic incentives. Due to uncertainties in these factors, gas supply projections for the United States in the year 2000 vary from 15 percent less to 50 percent more than present levels. All of these projections include some NG imports. Future domestic production will require recovery from increasingly inaccessible formations and hostile environments, and perhaps production of SNG from coal, wood, or municipal solid waste.

- The United States has sufficient proved and potential gas reserves, plus an SNG resource base, to support consumption near current levels through the rest of the century. If automotive gas use is confined to fleets, the additional demand is projected to be within the supply system's capability.

- Methanol supply forecasts are even more uncertain than NG projections. Methanol demand is forecasted to increase almost fivefold by the year 2000, mostly due to new applications, including fuel and fuel additive uses. Production of methanol from coal might then become economically attractive, but the required plants have a long construction lead time and cannot make a significant contribution until the 1990s. In the near-term, any supply shortfall would have to be covered by imports. Conversion of all SI fleet vehicles to methanol would require far more methanol than is available now or expected to be available in the near term.

- On average, CNG and LNG now have a net price advantage over gasoline of about $0.65 per equivalent gallon. This differential is expected to remain relatively constant during the 1980s and then increase significantly after 1990 because of relatively stable gas prices during a period when petroleum prices start to escalate rapidly. The prices of CNG and LNG produced from coal are projected to be 11 to 17 percent higher than if made from NG.

- Methanol now costs about $0.53 more than gasoline, per energy-equivalent gallon. Methanol from coal is expected to cost about 36 percent less than methanol from NG, as a result of the predicted lower cost of coal and the economies of scale of large coal conversion plants. It should then cost about $0.51 less than gasoline, per equivalent gallon. However, no such production facilities have been constructed as yet, and thus the predicted prices for coal-derived fuels remain to be verified.

VEHICLE SAFETY

- No fundamental safety problems exist with NG. Domestic and foreign NG vehicles have a generally good safety record. However, uncertainties exist because of insufficient data regarding crashworthiness, fire safety, and internal tank corrosion resistance of current NG vehicles.

- On balance, methanol system safety is expected to be comparable to that of gasoline systems, with advantages and disadvantages in various specific areas.

USER ECONOMICS

- Public NG fueling stations do not presently exist in the United States, and large capital investments in fueling station equipment would be required by NG users. Until this situation changes, NG conversions probably cannot be justified on economic grounds alone for family cars or very small fleets.

- A definitive general conclusion regarding the economic attractiveness of NG is precluded by wide application-to-application variations, and by uncertainties in key economic parameters. However, analyses performed in this study indicate that, in many cases, potentially attractive before-tax payback periods of about 1 to 4 years can be attained for moderate-size fleets.

- Methanol is not economically attractive to the user at the present time. If the projected low price of methanol produced from coal becomes a reality, then potentially attractive payback periods of about 1 to 2 years can be achieved in any size fleet.

RESEARCH NEEDS

- Industry has made significant progress in implementing methane-related fuels. However, testing is needed to conclusively define the efficiency, emissions, and performance of NG and methanol vehicles, and development of practical conversion systems for diesel vehicles is needed. In addition, fundamental work on high-energy-density adsorptive gas storage systems should be encouraged.

- A test program to determine crashworthiness and fire safety of state-of-the-art NG vehicles is needed, and various CNG tank designs should be evaluated for resistance to internal corrosion potentially caused by NG impurities.

- Assessments should be made of institutional barriers to NG and methanol use in vehicles, of NG use in stationary applications, and of the benefits of NG vehicles compared with electric vehicles.

1. INTRODUCTION

The goal of energy independence leads inevitably to consideration of alternative transportation fuels which can be produced in large quantities from domestic resources. Extensive foreign experience and limited domestic usage show that methane can be used as a fuel for automotive spark-ignition (SI) engines. The term methane, as used in this report, includes and is interchangeable with natural gas (NG) as well as synthetic (or substitute) natural gas (SNG) derived from coal, biomass, waste products or other renewable resources, provided methane is the predominant constituent. As a fuel currently available in large quantities and distributed nationwide through a million-mile pipeline network, NG warrants consideration for a wider role as an automotive fuel.

On December 12, 1980, Public Law 96-512, the Methane Transportation Research, Development, and Demonstration Act of 1980, was signed into law. Its primary purpose is to initiate an active program under the direction of the Department of Energy (DOE) to enhance the utilization of methane fuel in automotive fleet vehicles and farm equipment. In anticipation of this role, the DOE Office of Vehicle and Engine R&D conducted a workshop in August 1980 to identify pertinent topics for the assessment of methane as a fuel for automotive vehicle fleets. The resulting statement of work is composed of two phases. Phase I consists of five assessment tasks, which are addressed in this report: fuel economy and exhaust emissions, energy efficiency for transportation systems, gas supply, vehicle safety, and end-use economics. Phase II activities, which include the examination of institutional barriers, energy efficiency for alternative uses, an energy efficiency comparison with electric vehicles, and the conduct of additional vehicle tests, were deferred and are not covered in this report. Methanol was included in Phase I because it is a liquid fuel that can be synthesized from NG and other resources, and because it allows the use of fueling facilities and fuel systems which are similar in

design to those for gasoline, differing mainly in their use of alternative materials.

The approach selected for this study featured an extensive review of the open technical literature, supplemented by numerous discussions with manufacturers of automotive NG systems and components, fleet operators, researchers, and government personnel. In addition, two late-model automobiles, equipped with SI engines converted to compressed natural gas (CNG), were tested to determine their performance, fuel economy, and exhaust emission characteristics relative to operation on gasoline. During the course of this effort, three bimonthly meetings were conducted to inform interested industry and government organizations of study progress and to solicit technical information for use in the study.

2. FUEL SYSTEM TECHNOLOGY

Currently, the only practical forms of NG for vehicular usage are as a high-pressure gas and as a low-temperature cryogenic liquid. CNG has been used as a fuel for SI engines in approximately 275,000 privately owned and fleet vehicles in Italy for almost four decades. Domestic usage has reached about 20,000 fleet vehicles over the last decade. Several thousand vehicles in France, Canada, Iran, and other countries also use CNG, and New Zealand plans to convert 150,000 fleet and individually owned vehicles to NG use by 1985. About 200 SI fleet vehicles, primarily in the United States, are utilizing liquefied natural gas (LNG). Methanol is widely used in race cars, and over 100 methanol fleet vehicles are presently being evaluated in California.

This section describes current fuel system technology for vehicle application of NG and methanol. Vehicle systems considered include CNG and LNG dual-fuel (NG and gasoline) conversions and LNG and methanol single-fuel conversions.

2.1 VEHICLE SYSTEMS

The most widely used dual-fuel CNG system domestically available today for SI engines is illustrated in Figure 1. Automotive CNG systems typically use two or more heavy-wall, high-pressure (2400 psig) steel storage cylinders. Generally, these cylinders are mounted transversely in the trunk of a car, in the front of a pickup truck bed, or beneath the bed of a truck or trailer. The system is usually filled through a line from the engine compartment, and the same line allows gas flow from the cylinders to the engine. In operation, gas pressure is reduced by pressure regulators to near atmospheric, and the gas is admitted either into a separate gas-air mixer or into the carburetor venturis.

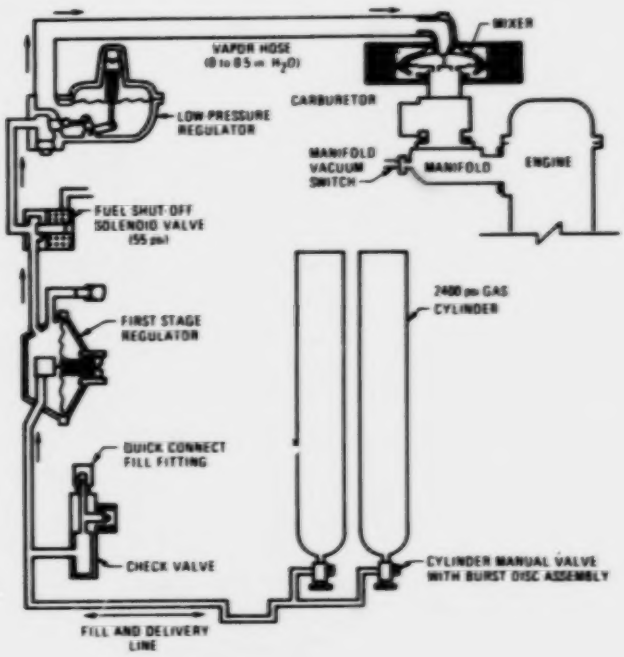

Figure 1. Vehicular CNG System Schematic (Courtesy of Dual Fuel Systems, Inc.)

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Figure 2 shows a schematic of an LNG system which has been used for a number of years in single- and dual-fuel SI-engine-powered cars and trucks. Alternative LNG systems differ primarily in their tank configuration, holding time before pressure relief, and fuel withdrawal controls. Usually, LNG storage systems consist of a single vacuum-insulated cryogenic liquid tank and associated controls, often fueled through a short line to minimize or eliminate fuel boiloff. In operation, the LNG is vaporized and heated to prevent ice formation in the mixer and intake system, and the gas is admitted to a gas-air mixer for induction into the engine.

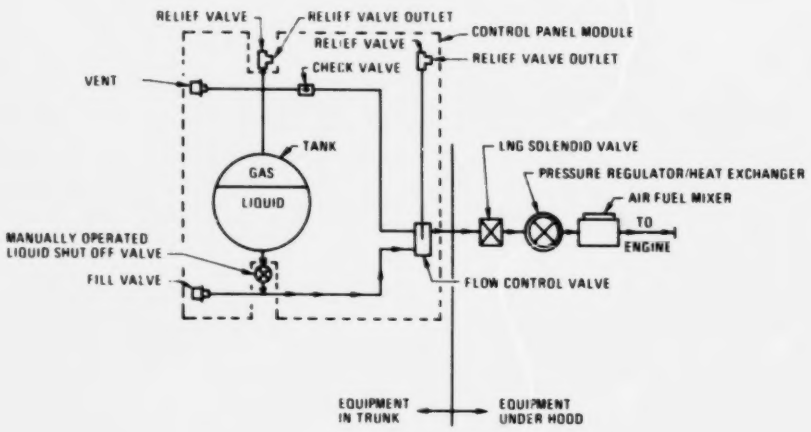

Figure 2. Vehicular LNG System Schematic
(Courtesy of Essex Cryogenics)

For methanol, fuel system material changes, larger carburetor jets, and provisions for cold start and improved fuel vaporization are required at a minimum. Otherwise, the fuel system is much like a conventional gasoline system. However, a fuel tank 50 to 100 percent larger than the gasoline tank is required if equal driving range is desired.

The only systems produced in commercial quantities to date in the United States are retrofit CNG and LNG systems for carbureted SI

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engines. Developers and marketers of automotive CNG conversion systems and fueling station equipment include Advanced Fuel Systems, Inc.; CNG Fuel Systems, Ltd. of Canada; CNG Services, Inc.; Dual Fuel Systems, Inc.; Dual Energy, Inc.; Essex Cryogenics of Missouri, Inc.; Gas Service Energy Corporation; and various Italian manufacturers. Beech Aircraft Corporation currently markets LNG conversion systems, and so reportedly do LNG Services, Inc. and others. Previous manufacturers and others interested in re-entering an expanded market include Essex Cryogenics of Missouri, Inc.; Gibson Cryogenics; and Kaiser Electro Precision Division.

Although no kits for conversion of vehicular diesel engines are commercially available in the United States, a variety of fuel admission techniques could be used including induction of gas with the intake air (fumigation), manifold injection, and direct cylinder injection. However, ignition aids would be required because of the low cetane number of methane and methanol. Conversions are commercially available for some stationary industrial diesel engines.

Table 1 presents a weight comparison of typical CNG and LNG components and systems currently available. Conversion of a car to dual-fuel CNG operation adds about 284 lb to vehicle weight, while a typical dual-fuel LNG conversion adds about 177 lb. For single-fuel conversions, the net weight effect is less because the gasoline fuel system can be removed. Efforts are underway by a number of manufacturers to improve tankage systems, primarily through reductions in weight and volume. CNG tank weight can be approximately halved through the use of composite structural materials. Cylinder volume can be reduced through use of higher storage pressures, but compression requirements are adversely affected. LNG tanks can be made more compact and lighter through the use of more ideal tank shapes, better material combinations, and more effective insulation systems. For example, Beech Aircraft reportedly has an aluminum LNG tank design which results in a total fuel system weight lower than that of the gasoline system it replaces.

Table 1. Weights of Typical Natural Gas Systems for Light-Duty Vehicles

SYSTEM COMPONENT[1]	WEIGHT, LB CNG	WEIGHT, LB LNG
ENERGY STORAGE		
TWO 325 SCF STEEL CYLINDERS	216	-
ONE 18 GAL STEEL CRYOGENIC CYLINDER	-	75
OTHER HARDWARE		
MOUNTING BRACKETS	10	10
PRESSURE REGULATOR & SOLENOID VALVE	15	15
HEAT EXCHANGER	-	
GAS-AIR MIXER & CARBURETOR ADAPTER	10	10
FUEL GAUGE AND SWITCH ASSEMBLY[2]	2	1
LINES, FITTINGS, VALVES & CONNECTORS	2	2
TOTAL OTHER	39	38
FUEL	29	64
TOTAL	284	177

(1) VEHICLE RANGE TYPICALLY 60-120 MI FOR CNG (IN ADDITION TO GASOLINE RANGE IN DUAL-FUEL VEHICLES), AND 200-400 MI FOR LNG.
(2) DUAL-FUEL SYSTEMS ONLY.

CNG conversion kits with two steel cylinders are currently available from at least five domestic suppliers for $1100 to $1600, excluding installation, taxes, and freight costs. Vehicle installation costs $150 to $250 and requires 8 to 12 man-hours. With an 18-gallon cryogenic tank, LNG kit cost is $1500 to $1800, with an additional $150 to $250 for installation. However, suppliers and developers indicate a strong sensitivity of system cost to the required tank standby time before venting, and to crashworthiness specifications. It should be noted that these costs are initial conversion costs. Many current CNG and LNG conversion system components have a long life, which allows their transfer from old to new vehicles with little or no rework.

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Because of weight and volume considerations, typical two-cylinder dual-fuel CNG systems add only 60 to 120 miles to the range of cars and light-duty trucks. Conversely, LNG systems are more compact and can be used readily in single-fuel applications, typically providing a range of 200 to 400 miles.

Methanol conversions are available commercially for SI engines from at least one supplier. In addition, recent development and demonstration work by Ford Motor Company and Volkswagen indicates that factory-built methanol vehicles could become available commercially.

2.2 FUELING STATIONS

Most equipment manufacturers agree that safe and economical operation of currently available CNG and LNG fueling equipment can best be accomplished at fleet garages or large public stations with trained operators. In the United States, only the fleet approach has been used to date. However, in Italy approximately 220 public CNG fueling stations have been in use for many years. Domestically, public stations are being considered seriously by CNG Services, Inc. and others, but the number of CNG or LNG vehicles would have to increase substantially from current levels for this approach to achieve more than localized success.

In the United States, two general approaches to CNG vehicle fueling are employed. Often available from the same station, the methods are (1) slow-filling, or time-filling, of one or more vehicles directly from a high-pressure compressor, and (2) fast-filling of vehicles from a cascade of high-pressure cylinders previously filled by a compressor. Typically, time-filling requires up to 14 hours, while fast-filling is accomplished in 2 to 5 minutes. Figure 3 depicts the principal components of a typical combined system. The fast-fill section consists of one or more multistage compressors which deliver CNG at approximately 3600 psig to individual cascades. The stored CNG is delivered to the vehicles in a controlled manner through a set of fill hoses. The time-fill section of the station employs a high-pressure manifold and a number of fill-post or hose-drop assemblies.

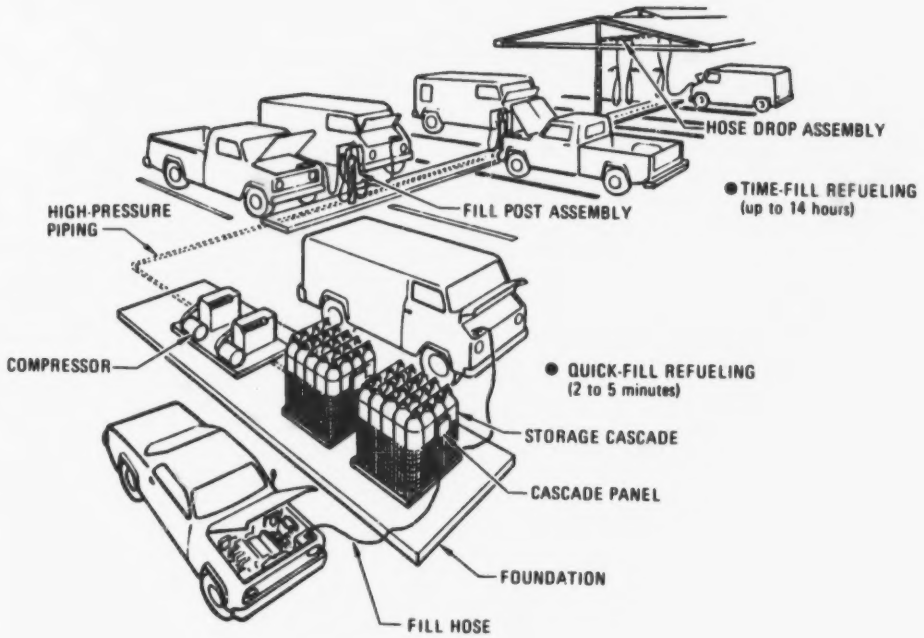

Figure 3. CNG Fleet Fueling Station (Courtesy of Dual Fuel Systems, Inc.)

Principal station design considerations are the number of CNG fillings required daily, available parking space, and equipment and facility costs. The compressor is the key component affecting initial cost, operating cost, and maintenance requirements. Domestically marketed CNG compressors currently range in capacity from 3.5 to 100 standard cubic feet per minute (scfm), which is equivalent in energy to about 2 to 50 gallons of gasoline per hour. Smaller units are under development for use by small fleets or individual users. Compressor cost increases almost linearly with capacity for sizes over 3.5 scfm, up to about $70,000 at 100 scfm. Station cost is affected by other factors, including the requirements for indoor or outdoor parking, electric power lines, barrier walls, and automatic leak detection equipment and controls. Total investment cost for a typical 50 scfm station ranges from about $60,000 to $100,000.

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LNG fueling stations generally can fill several vehicles simultaneously from an LNG bulk storage tank. The latter can be periodically replenished through a vacuum-insulated pipeline from a liquefaction plant, or by truck or rail transport. A typical LNG station consists of a bulk storage tank and its controls, a fuel transfer system, vehicle couplings, and a vapor disposal system.

The LNG storage tank is the principal contributor to fueling station cost. In 1979, one source projected a cost of approximately $110,000 for a complete 10,000 gallon station. Unlike CNG stations, the cost of LNG stations declines slowly as fuel capacity is reduced. Only one LNG station, operated by Atlanta Gas Light Company, is known to be serving an operating vehicle fleet in the United States, but several others may have been activated in recent months to service experimental LNG systems manufactured by Beech Aircraft Corporation and others.

At this time there are no known domestic stations dispensing methanol fuel, except those set up for the support of methanol vehicle test fleets in California. One source estimates a methanol station cost of $30,000 to $60,000 if new tanks and dispensing equipment are used. For retrofit conversions, which do not require new storage tanks, station costs should be considerably less.

3. VEHICLE OPERATION

In theory, both NG and methanol possess a number of very desirable characteristics as automotive engine fuels. However, to take full advantage of each fuel's attributes while minimizing its disadvantages requires major modifications to a vehicle optimized for gasoline, and in practice this is rarely done. This section discusses the effects of NG and methanol on vehicle operation from a theoretical viewpoint and in terms of available laboratory and fleet test data.

3.1 NATURAL GAS ADVANTAGES AND DISADVANTAGES

In principle, NG lends itself well to use in SI engines. The primary advantage of NG as an SI-engine fuel is its high octane number compared with present-day gasoline, which in single-fuel applications permits the use of high compression ratios, with accompanying efficiency and performance benefits. In addition, the broad flammability limits of NG allow engine operation at lean air-fuel mixtures, which further improves thermal efficiency. Much of the total hydrocarbons (HC) emitted consist of environmentally benign non-reactive methane. This is particularly encouraging in view of the Environmental Protection Agency (EPA) Notice of Proposed Rulemaking for amending vehicle emission standards to permit compliance with a non-methane hydrocarbon standard (46-FR-62366; December 23, 1981). Emissions of carbon monoxide (CO) and oxides of nitrogen (NO_x) tend to be lower than for gasoline, primarily as a result of leaner engine operation. Additional benefits are related to the gaseous state of NG, which improves cylinder-to-cylinder fuel distribution and reduces engine throttling losses.

In addition to the problem of on-board fuel storage, NG has several disadvantages as an automotive fuel. Its gaseous state tends to result in reduced wide-open-throttle engine power because the NG displaces intake air. Lean operation aggravates the power loss, but mixture enrichment at full load can be employed to avoid this effect. Also, in the case of LNG, the heat of vaporization of the fuel can potentially be used for intake air cooling, to increase volumetric efficiency. Another disadvantage of NG is its low flame speed, which tends to result in decreased engine thermal efficiency, although part of this loss may be recovered by means of spark timing optimization, at the expense of an increase in NO_x and HC emissions. The low cetane number of NG makes it unsuitable as the sole fuel for unmodified conventional diesel engines, although its use is possible in conjunction with supplementary ignition aids.

3.2 NATURAL GAS VEHICLE TEST DATA

In practice, fuel economy, performance, and emissions of NG-fueled vehicles are affected by the degree to which the engine calibration and system hardware have been optimized to take advantage of the favorable characteristics of NG relative to gasoline. Vehicle fuel economy further depends on the level of performance, emissions, and driving range deemed acceptable, since all of these can be traded off for fuel economy to some extent with any fuel. When fully optimized, engine efficiency gains of about 20 percent appear to be possible. However, since most available vehicle data are not based on fully optimized systems and comparable vehicle performance, emissions, and driving range, a conclusive assessment of the ultimate potential of NG as an automotive fuel is not possible at this time.

Fuel economy and performance test data from NG-fueled fleet and experimental vehicles are summarized in Tables 2 and 3. Most of these are dual-fuel vehicles, with generally non-optimal spark timing and air-fuel ratios. Fleet operators reported gasoline-equivalent fuel economy changes for operation on NG ranging from a 30 percent decrease to a 42 percent increase relative to similar vehicles operated on gasoline. Frequently, questionable energy equivalency factors are used by fleet operators to compare NG and gasoline fuel economy, and this undoubtedly contributes to the spread in the reported fuel economy values. Other factors contributing to the large fuel economy variability are (1) differences in driving cycles, (2) variations in the degree of engine optimization, and (3) use of some baseline vehicles in which fuel economy was compromised to meet emission standards and driveability requirements.

Although the experimental vehicle data are based on more controlled conditions, they also show no conclusive efficiency effect for NG operation. However, the vehicles tested do not reflect fully-optimized configurations for NG. Tests performed during the course of this study indicate approximately equal energy-equivalent fuel economy for NG and gasoline in tests without spark timing modifications. In all cases, engine

Table 2. Summary of Natural Gas Vehicle Data - Fleet Operators

ORGANIZATION	VEHICLE MODEL YEARS	VEHICLE TYPES	PERCENTAGE CHANGE POWER	PERCENTAGE CHANGE FUEL ECONOMY	ASSUMED ENERGY EQUIVALENCE, SCF/GAL
CNG					
ARA, INC.	'66 TO '81	SERVICE	DECREASE	+10	100
BATTLE CREEK GAS CO.	'73 TO '81	SERVICE	-	+17	130
EATON SCHOOL DISTRICT	'69 TO '79	BUSES	DECREASE	+31	126
GENERAL SERVICES ADMIN.	'68 TO '69	SERVICE	DECREASE	+11	120
CITY OF GREELEY	-	-	-	+ 4	100
MICH. CONSOLIDATED GAS CO.	1969	SERVICE	DECREASE	+ 2	125
SEDGWICK COUNTY	1980	POLICE	DECREASE	-17	100
SHAWNEE COUNTY	1980	POLICE	DECREASE	-30	100
SOUTHERN CALIF. GAS CO.	'67 TO '69	-	-	+ 5	114
WASHINGTON GAS LIGHT CO.	-	SERVICE	-	-	113
WELLINGTON GAS CO.	'74 TO '78	SERVICE	-18	+13	108
YELLOW CAB CO.	-	TAXI	-	-12	-
LNG					
ATLANTA GAS LIGHT CO.	'74 TO '81	SERVICE	DECREASE	+42	-

Table 3. Summary of Natural Gas Vehicle Data - Experimental Vehicles

ORGANIZATION	VEHICLE MODEL YEARS	VEHICLE TYPES	PERCENTAGE CHANGE POWER	PERCENTAGE CHANGE FUEL ECONOMY	ASSUMED ENERGY EQUIVALENCE, SCF/GAL
CNG					
DOE/BETC	1978	LDV	-	+1	104
DOE/BUREAU OF MINES	'68 TO '70	LDV	DECREASE	DECREASE	-
DOE/EPA	'79 TO '80	LDV	-27	+1	130
DUAL FUEL SYSTEMS, INC.	'77 TO '81	LDV/MD	-	-1	126
GENERAL MOTORS	1967	LDV	-15	-	-
LNG					
BEECH AIRCRAFT CORP.	1980	LDV	DECREASE	DECREASE	-
SHELL RESEARCH	1970	LDV	-24	+13	-

power was sacrificed with NG operation, and reported vehicle acceleration times increased by 20 to 45 percent. Since vehicle fuel economy can generally be traded for reduced performance with any fuel, the observed fuel economy changes overstate the beneficial effect attributable to NG alone.

Limited exhaust emission data available from fleet vehicle tests indicate emission reductions with CNG of about 45 to 60 percent for

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HC, 60 to 80 percent for CO, and 50 to 80 percent for NO_x. Conversely, the experimental NG vehicles, most of which are catalyst equipped, generally show increases in total HC relative to their gasoline counterparts. This is primarily because current automotive catalysts are relatively ineffective in oxidizing non-reactive methane, the primary HC species emitted from NG-fueled engines.

NG has a very low cetane number, and therefore is unsuited as the sole fuel for unmodified conventional diesel engines. However, in conjunction with chemical or thermal ignition aids, NG may be used in diesels, although to date its application has been restricted to stationary, marine, and laboratory applications. Chemical ignition aids under consideration include direct pilot injection of small quantities of an easily ignitable fuel, such as diesel fuel. The NG either is injected directly into the cylinders or more commonly fumigated, i.e., mixed with air and inducted via the intake manifold. Thermal ignition aids potentially applicable to diesel engines include spark plugs and glow plugs. While these techniques are technically feasible in principle, they are not proven for automotive retrofit applications.

Because of its simplicity and relative ease of implementation in diesel retrofit application, NG fumigation in conjunction with pilot injection of diesel fuel is currently favored by most investigators. Relative to direct injection of NG, fumigation increases air utilization and has the potential for lower smoke emissions, thereby permitting an increase in smoke-limited engine power. Relative to engine operation on diesel fuel only, NG fumigation generally results in an increase in total HC and CO emissions, and a decrease in NO_x at part load. Much of the HC probably is methane. Both CO and HC emissions tend to further increase at low load, unless the mass ratio of pilot fuel to NG is carefully regulated to prevent lean flameout in the bulk air-fuel mixture.

3.3 NATURAL GAS OPERATIONAL EXPERIENCE

Operational experience with NG relative to gasoline is summarized in Table 4, as reported by organizations using CNG and LNG systems. The problems associated with CNG cylinder weight and engine power loss are expected to become less significant as technological advancements are made. However, problems caused by cylinder volume requirements may become relatively more severe as automobile downsizing continues.

Table 4. Operational Experience with Natural-Gas-Fueled Vehicles

ADVANTAGES	DISADVANTAGES
GREATLY REDUCED FUEL COSTS	GREATLY REDUCED DRIVING RANGE ON CNG
ENGINE LIFETIME EXTENDED	REDUCED ENGINE POWER REQUIRES LARGER ENGINES, HIGHER NUMERICAL FINAL DRIVE RATIO
EASY STARTING AND ENHANCED COLD-START DRIVEABILITY	CYLINDER WEIGHT AFFECTS STEERING AND MAY REQUIRE SUSPENSION CHANGES
SUBSTANTIALLY INCREASED SPARK PLUG LIFE	CYLINDERS OCCUPY NEEDED TRUNK SPACE
OIL CHANGE INTERVALS EXTENDED TO 25,000 MI	FREQUENT ENGINE/CNG SYSTEM TUNING FOR GOOD PERFORMANCE
REDUCED ENGINE MAINTENANCE BECAUSE OF NO CARBON BUILDUP	ENGINE KNOCKING IN GASOLINE MODE
REDUCED FUEL PILFERAGE	

3.4 METHANOL VEHICLE CHARACTERISTICS

The basic technical feasibility of methanol as a fuel for spark-ignition engines is well established. In general, engine power increases with methanol, and satisfactory cold-start characteristics have been demonstrated with various techniques, ranging from fuel additives to add-on hardware. Methanol is a commonly used racing fuel, and passenger car field tests are currently under way.

Similar to NG, energy economy with methanol depends on the degree to which the engine is modified to take advantage of the high octane number, broad flammability limits, high flame speed, and other favorable characteristics of this fuel. With carburetor and spark timing

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changes only, there may be little or no energy economy benefit. The use of increased engine compression ratio, combined with optimized spark timing and air-fuel ratio, results in energy-equivalent fuel economy gains of 20 percent or more. However, since methanol has only about half as much energy per gallon as gasoline, fuel economy on a volume or mass basis is significantly lower with methanol.

Emissions of HC and CO are approximately equal to those for gasoline, while NO_x emissions tend to be significantly lower. Conversely, engine-out emissions of aldehydes, a presently unregulated pollutant species, are much higher with methanol. Although the catalysts used in current emission control systems are very effective in oxidizing aldehydes when fully warmed up, cold-start emissions may present a problem. By exploiting the lean-burn capability of methanol, emissions of HC and CO pollutants can also be lowered relative to gasoline.

The feasibility of methanol as a practical diesel fuel has not been adequately established. The ignition quality of methanol is extremely low, and thermal or chemical ignition aids are required to achieve acceptable engine operation. Glow plugs, spark assistance, pilot injection, and chemical additives are being investigated, but all represent added cost and complexity. Compared with an optimized high-compression-ratio methanol SI engine, the typical efficiency advantage of the diesel engine is greatly diminished, and the energy benefits of methanol use in this application are questionable on an original equipment basis.

4. RESOURCE ENERGY UTILIZATION

Resource energy utilization is one basis for comparing alternative fuels, since it includes consideration of the fuel supply logistic chain as well as vehicle energy requirements. The logistic chain efficiency is the product of the efficiencies for extraction, preparation, chemical conversion, product cleanup, storage, transportation, distribu-

tion, compression or liquefaction, and dispensing. It is essentially independent of the end use. Conversely, vehicle energy requirements are impacted by the engine efficiency characteristics with each fuel, by vehicle weight, and by vehicle mission constraints regarding performance, driving range, and emissions. This section compares the logistic chain efficiencies and vehicle energy requirements with NG, methanol, and conventional fuels, and assesses their relative resource energy utilization in vehicle applications.

4.1 LOGISTIC CHAIN EFFICIENCIES

Table 5 details the logistic chain efficiencies for three fuels produced from NG: CNG, LNG, and methanol. The efficiencies are defined on the basis of total energy input and output, without regard to the form of the energy. As illustrated, CNG has a clear advantage over the other two fuels.

Table 5. Logistic Chain Efficiency from Resource to Vehicle
Input -- Energy Resource: Natural Gas

PROCESS	PROCESS EFFICIENCY		
	CNG	LNG	METHANOL
EXTRACTION/GATHERING	0.964	0.964	0.964
PREPARATION/PROCESSING	0.968	0.968	0.968
CONVERSION	NA	NA	0.64
TRANSPORT	0.95	0.95	0.98
PRODUCT CLEANUP / LIQUEFACTION	NA	0.86	NA
STORAGE	0.996	0.997	1.00
DISTRIBUTION	0.993	0.99	0.98
COMPRESSION	0.89-0.98	NA	NA
DISPENSING	1.00	0.98	0.99
TOTAL	0.78-0.86	0.74	0.57

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The logistic chain efficiencies for fuels produced from a variety of resources are shown in Table 6. CNG from conventional NG appears to be the only fuel competitive with gasoline and diesel fuel, with methanol from any source significantly less efficient. Production of methanol from coal is about as efficient as production of CNG from coal, and slightly less efficient than production of methanol from conventional NG.

Table 6. Logistic Chain Efficiency from Resource to Vehicle Input

FINISHED FUEL	LOGISTIC CHAIN EFFICIENCY FROM RESOURCE				
	PETROLEUM	NATURAL GAS	COAL	WOOD	MSW
GASOLINE	0.84	-	-	-	-
DIESEL FUEL	0.86	-	-	-	-
COMPRESSED NATURAL GAS	-	0.78-0.86	0.51-0.56	0.48-0.53	0.43-0.47
LIQUEFIED NATURAL GAS	-	0.74	0.48	0.45	0.40
METHANOL	-	0.57	0.55	0.50	0.38

4.2 VEHICLE ENERGY REQUIREMENTS

Table 7 illustrates the effects of different dual- and single-fuel systems on vehicle characteristics, based on a typical 1981 sub-compact vehicle. For the analysis, performance and fuel economy were calculated using influence coefficients derived from computer simulations. The dual-fuel NG cars reflect conversions which employ unaltered engine compression ratios and spark timing, and their engine thermal efficiency was estimated to be equal to that of the baseline. However, calculated energy economy and performance are lower than the baseline, because of increased vehicle weight and decreased engine power. Vehicle driving range improves because the gasoline tank was left intact. For equal driving range and performance, which is the proper comparison basis, energy consumption of the dual-fuel cars is higher than that of the baseline gasoline vehicle by 54 and 35 percent for CNG and LNG systems, respectively.

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Table 7. Simulation Results for Light-Duty Spark-Ignition Alternative-Fuel Vehicles

VEHICLE CHARACTERISTICS	GASOLINE BASELINE	DUAL-FUEL CNG	DUAL-FUEL LNG	SINGLE-FUEL CNG	SINGLE-FUEL LNG	SINGLE-FUEL METHANOL
RETROFIT CONVERSIONS						
OPERATING CHARACTERISTICS						
CITY FUEL ECONOMY, MPG_E	28.0	26.3	26.9	28.7	33.7	33.1
0-60 MPH ACCELERATION TIME, SEC	17.6	28.0	26.9	20.6	15.7	14.1
DRIVING RANGE, MI	350	429	659	350	350	350
VEHICLE ASSUMPTIONS						
INERTIA WEIGHT, LB	2356	2552	2487	2977	2421	2399
AVAILABLE ENGINE POWER, BHP	69.0	51.8	51.8	77.3	77.3	82.8
GASOLINE TANK CAPACITY, GAL	12.5	12.5	12.5	0	0	0
ALTERNATIVE FUEL TANK CAPACITY, GAL (SCF)	0	(477)	18.0	(1525)	15.6	21.5
COMPARABLE VEHICLES						
OPERATING CHARACTERISTICS						
CITY FUEL ECONOMY, MPG_E	28.0	18.2	20.7	25.4	36.0	37.1
0-60 MPH ACCELERATION TIME, SEC	17.6	17.6	17.6	17.6	17.6	17.6
DRIVING RANGE, MI	350	350	350	350	350	350
VEHICLE ASSUMPTIONS						
INERTIA WEIGHT, LB	2356	2857	2603	3104	2382	2345
AVAILABLE ENGINE POWER, BHP	69.0	83.7	76.2	90.9	69.8	68.7
GASOLINE TANK CAPACITY, GAL	12.5	13.8	0	0	0	0
ALTERNATIVE FUEL TANK CAPACITY, GAL (SCF)	0	(688)	25.4	(1724)	14.6	19.2

The single-fuel cars use optimized engine configurations and smaller fuel tanks. In contrast to the dual-fuel vehicles, the retrofit single-fuel CNG, LNG and methanol cars consume about 3, 17, and 16 percent less energy, respectively, than the baseline gasoline vehicle. On a comparable performance and driving range basis, the single-fuel CNG vehicle uses 10 percent more energy, while the LNG and methanol vehicles use 22 and 24 percent less, respectively. A similiar analysis for diesel cars and for SI and diesel trucks is presented in Volume II.

4.3 OVERALL RESOURCE ENERGY CONSUMPTION

When the logistic chain efficiencies from Table 6 are combined with the energy consumption characteristics of Table 7, the resource energy consumption values of Table 8 are obtained for retrofit alternative-fuel vehicles. With NG as the resource, only the single-fuel LNG system clearly consumes less resource energy than the gasoline baseline. This is accomplished while matching the range and exceeding the acceleration

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Table 8. Overall Resource Consumption for Light-Duty SI-Engine Vehicles

	RESOURCE CONSUMPTION[1], BTU/MI				
	DUAL-FUEL		SINGLE-FUEL		
RESOURCE	CNG	LNG	CNG	LNG	METHANOL
NATURAL GAS	5700-6200	6500	5200-5700	5100	7000
COAL	8700-9500	10,000	8000-8700	7900	7200
WOOD	9200-10,100	10,600	8400-9300	8500	8000
MSW	10,300-11,300	12,000	9500-10,400	9500	10,500

(1) BASELINE VEHICLE CONSUMES 5278 BTU/MI.

capability of the baseline vehicle. The methanol vehicle system, even in its optimized single-fuel configuration, requires the highest amount of resource energy.

With coal, wood, and municipal solid waste (MSW), resource energy requirements are higher than with NG by up to 100 percent. For coal and wood, a single-fuel methanol system appears to be the most effective. For MSW, the single-fuel LNG system is superior to the others by at least 10 percent.

Analysis of CNG, LNG, and methanol use in diesel-powered automobiles and trucks also indicates that, if conversions become available, large increases in resource energy consumption would result for all vehicles except large trucks, as detailed in Volume II. Relative to operation on diesel fuel, these fuels result in higher fuel system weights, lower logistic chain efficiencies, and higher resource energy consumption.

5. POTENTIAL PETROLEUM DISPLACEMENT

This section assesses the amount of petroleum-based fuel which potentially could be displaced by CNG, LNG, and methanol use in fleets.

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Baseline fuel consumption was projected using statistical data that include number of vehicles, average annual mileage, and fuel consumption by vehicle and fuel type. Where possible, these data were projected through the year 2000.

The projected fuel consumption for major fleet categories is shown in Table 9. It is also shown for "large" fleets of 10 or more cars, or 6 or more trucks. The fleet cutoff sizes were selected based on data availability and preliminary economic payback considerations. Gasoline consumption of car fleets is projected to decline substantially by the year 2000, while diesel fuel consumption is expected to increase ten-fold. Gasoline consumption by "large" truck fleets is projected to diminish, and diesel engines are expected to become predominant in these applications.

Table 9. Projected Petroleum-Based Fuel Consumption

	PETROLEUM-BASED FUEL CONSUMPTION, 10^9 GAL/YR							
	1977-1981[1]		1985		1990		2000	
VEHICLE TYPE	GASOLINE	DIESEL	GASOLINE	DIESEL	GASOLINE	DIESEL	GASOLINE	DIESEL
FLEET AUTOMOBILES	15.37	0.58	12.0	1.7	9.9	3.9	8.9	5.5
FLEETS OF TEN OR MORE	5.91	0.22	4.6	0.6	3.8	1.5	3.5	2.1
PRIVATE AND COMMERCIAL TRUCKS	23.56	9.23	25.0	19.2	23.4	27.6	21.6	44.3
FLEETS OF SIX OR MORE	4.06	6.06	3.9	11.8	3.2	15.6	2.2	22.5
GOVERNMENT TRUCKS								
FEDERAL	0.23 COMBINED							
STATE AND LOCAL	UNKNOWN							
BUSES			NO PROJECTIONS AVAILABLE					
TRANSIT AND INTERCITY	0.01	0.60						
SCHOOL	0.41	0						

(1) DATA ARE FOR VARIOUS YEARS.

Table 10 shows estimates of potential displacement of petroleum-based fuels by NG in 1985. The petroleum-displacement factor is the product of (1) "large" fleet fuel consumption as a fraction of the fleet total, and (2) petroleum-based fuel displaced per affected vehicle as a fraction of the baseline. The latter factor was estimated to be about 95 percent of baseline gasoline consumption, and 42 to 76 percent of

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Table 10. Potential Petroleum-Based Fuel Displacement in 1985 by Natural Gas Fleet Cars and Private and Commercial Trucks

VEHICLE TYPE	NUMBER, MILLIONS	1985 FUEL CONSUMPTION, 10^9 GAL		CNG OR LNG PET. DISPL. FACTORS		POTENTIAL PETROLEUM-BASED FUEL DISPLACED, 10^9 GAL		
		GASOLINE	DIESEL	GASOLINE	DIESEL	GASOLINE	DIESEL	TOTAL
FLEET CARS	13	12.0	1.7	0.36	0.16	4.32	0.27	4.59
PRIVATE & COML. TRUCKS								
LIGHT		21.3	1.2	0.09	0.03	1.92	0.04	1.96
MEDIUM		0.6	0.0	0.32	0.18	0.19	0.00	0.19
LIGHT-HEAVY		2.5	1.1	0.46	0.32	1.15	0.35	1.50
HEAVY-HEAVY		0.6	16.9	0.63	0.50	0.38	8.45	8.83
TOTAL TRUCKS	38	25.0	19.2			3.64	8.84	12.48
TOTAL	51	37.0	20.9	-	-	7.96	9.11	17.07
NOTE: COMBINED CARS & LIGHT TRUCKS	47	33.3	2.9	-	-	6.24	0.31	6.55

diesel fuel consumption, depending on the application. These displacement factors represent upper limits. There are disincentives which make complete NG conversion of all "large" fleets unlikely in the near- to mid-term. Among these are (1) reduced power output, (2) tank packaging requirements, (3) competing alternative fuels, (4) limited remaining useful life of existing vehicles, (5) uncertain equipment availability in required volume, (6) limited availability of funds, and (7) mission constraints precluding centralized fueling.

The principal conclusion from Table 10 is that trucks have a greater petroleum displacement potential than cars when the heavy-heavy Class 8 diesel trucks are included. Excluding Class 8 trucks, which are typically long-haul diesel vehicles and would require both technology advances and many fueling stations, only gasoline applications show significant petroleum displacement potential. If all "large" fleets were converted, the total petroleum displaced would be 17 billion gallons per year (GPY) in 1985, corresponding to about 16 percent of the projected highway vehicle total. Excluding diesel vehicles, which require technology advances to use NG, annual petroleum savings of about 8 billion GPY would result, or 8 percent of the projected total.

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If sufficient methanol were available, it could potentially displace 8 billion GPY of gasoline and, with technology advances, about 9 billion GPY of diesel fuel in 1985 from large fleets. These correspond to about 8 and 9 percent, respectively, of the projected highway vehicle total. However, the corresponding methanol production requirement of about 15 to 35 billion GPY far exceeds the projected supply.

6. FUEL SUPPLY

A key question regarding NG use in fleet vehicles is whether adequate supplies at acceptable prices will be available in the future. Domestic NG has sustained large fluctuations in availability since the late 1960s, a period of abundance and low prices, through industrial curtailments in the 1970s, to the increasing supplies and rising prices of recent months. Much of the improvement on the supply side has been due to the Natural Gas Policy Act (NGPA) of 1978. This Act provides for gradual price increases, particularly for gas discovered after the spring of 1977, with complete decontrol of the latter in 1985. Another major factor has been the decontrol of crude oil prices in early 1981, inasmuch as oil drillings have resulted in the discovery of many gas fields. The outlook for NG supplies has changed so radically during 1981 that plans for several supplemental sources of high-Btu gas from coal, such as the WyCoalGas Project, have been suspended at least temporarily.

6.1 DOMESTIC RESOURCE BASE

The United States possesses large proven and potential reserves of conventional NG located onshore and offshore, in the lower 48 states and Alaska. In addition, the in-place unconventional gas resource, composed of gas in coal seams, Devonian shale, tight gas reservoirs, and geopressured brines, is estimated to be larger than the conventional gas resource. Even though only a small portion of the unconventional gas may be economically recoverable, it could be a significant addition to the nation's future gas supply, as shown in Table 11. However, the values for

Table 11. Domestic Sources and Quantities of Natural Gas

CATEGORY	QUANTITY, TRILLION CUBIC FEET			
	PROVED RESERVES	POTENTIAL RESOURCES	ESTIMATED GAS IN-PLACE	ESTIMATED MAX. RECOVERABLE
CONVENTIONAL GAS	191	913	NA	NA
UNCONVENTIONAL GAS				
COAL SEAMS	NA	NA	400-500	10-60
DEVONIAN SHALE	NA	NA	400-2000	50
TIGHT GAS	NA	NA	800-925	600
GEOPRESSURED BRINES	NA	NA	1000-100.000	1-2000

conventional gas are much more certain than those for unconventional sources. Based on current domestic consumption of about 20 trillion cubic feet (TCF) per year, as reported by the DOE, it is apparent that there is potentially at least 50 years' worth of NG in the ground, although recovery may require advanced technologies and incur higher costs.

In addition, SNG and methanol can be made from several fossil and renewable materials, particularly coal, using existing technology. United States coal reserves and total resources are very large, and supply should not be a constraining factor for many decades. Construction of a 125 million cubic feet per day (0.05 TCF per year) SNG production plant based on coal has just been initiated in North Dakota.

Other potential domestic sources for SNG and methanol production include biomass, MSW, and animal residues. Process development for more cost-effective conversion of biomass and waste matter to SNG and methanol is still needed, in spite of significant research activity in these areas during the past decade. The economic feasibility and national contribution of these resources during the coming years are uncertain at this time, but local situations may make them attractive small-scale gas sources.

6.2 GAS SUPPLY FORECAST

Because of uncertainties in economics, technology, and government policy, forecasts of gas supplies for the remainder of this century

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vary widely, both in total gas quantities and individual source contributions. Table 12 shows projections by DOE in its 1980 Annual Report to Congress and by the American Gas Association (AGA), illustrating low and high estimates of future gas supplies. Other forecasts falling within this range have been made by Exxon Company, Shell Oil Company, and Data Resources, Incorporated.

Table 12. Projections of U.S. Gas Supply from All Sources

	PROJECTED U.S. GAS SUPPLY, TCF				
	1985	1990		2000	
SOURCE	DOE	DOE	AGA	DOE	AGA
DOMESTIC PRODUCTION					
CONVENTIONAL					
LOWER 48 STATES	15.8	13.3	15-17	10.4	12-14
ALASKA	0.0	0.9	0.8	1.3	1.5
ENHANCED RECOVERY	0.7	1.3	0.4-1.0	4.6	1.5-3.0
SNG FROM COAL	0.1	0.1	1.0	0.3	1.5-2.5
GAS FROM NAPHTHA, NGL	0.0	0.0	0.3	0.0	0.3
OTHER	0.0	0.0	0.2-0.6	0.0	1.0-2.5
SUBTOTAL	16.6	15.6	17.7-20.7	16.6	17.8-23.8
NET IMPORTS					
CANADIAN PIPELINES	0.6	0.1	1.7	0.0	2.0
MEXICAN PIPELINES	0.1	0.1	1.0	0.0	2.0
LNG SHIPS	0.8	0.8	1.5	0.6	2.5
SUBTOTAL	1.5	1.0	4.2	0.6	6.5
TOTAL SUPPLY	18.1	16.6	21.9-24.9	17.2	24.3-30.3

Almost all forecasts show declining conventional NG production from the lower 48 states, the current source of almost all NG in the United States. The decline has been somewhat alleviated over the past three years by a surge of drilling as a result of price incentives provided under the NGPA. Almost all projections include nearly one TCF per year of Alaskan gas starting in the 1985-86 time period. All estimates show an increasing contribution from unconventional gas sources and SNG from coal, but there are wide differences in the expected rates of growth. Another area of uncertainty is the future contribution of imported NG to domestic supplies, as shown in Table 12.

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Part of the disparity between the DOE and AGA projections results from the fact that the former is demand-constrained, while the latter is not. DOE forecasts lower demand for NG due to (1) conservation resulting from price increases, (2) restrictions on use, such as the Powerplant and Industrial Fuel Use Act of 1978, and (3) increasing use of low- and medium-Btu gas from coal in central power generation and in industry. The DOE forecast includes the assessment that more gas could be produced if needed.

Based on consideration of published forecasts, the most likely NG supply values lie between those projected by DOE and the lower end of the range estimated by AGA. This assessment implies that the supply until the end of the century will not depart significantly from the current consumption of 20 TCF per year, although the sources of NG will change substantially during that time period. If NG for automotive use is confined to SI fleet operations, the additional demand of about one TCF per year should be within the capability of the supply system.

6.3 METHANOL SUPPLY FORECAST

Projections for methanol availability are even more uncertain than for NG. Table 13 shows a recent forecast by Chem Systems, Incorporated, the most detailed currently available. However, new markets and new sources cloud both the demand and supply picture. If the predicted surge in methanol demand materializes, there will be a strong economic incentive to switch to coal as the preferred feedstock instead of NG. Domestic production capability could thereby be maintained, and costs would be controlled by lower raw material prices and savings accruing from very large-scale production plants. However, such coal conversion facilities cannot come onstream until the 1990s because of their long construction lead time. The near-term alternative supply source is foreign production plants that are expected to be constructed in areas of surplus NG, such as Indonesia and Saudi Arabia. In any case, conversion of all SI fleet vehicles to methanol use would require more than 15 billion GPY of methanol by 1985, and this far exceeds the present and projected supply.

Table 13. Projected Methanol Demand and Supply in the United States and the World

CATEGORY	PROJECTED METHANOL DEMAND/SUPPLY, 10^6 GAL/YR 1980 WORLD	1980 U.S.	1990 WORLD	1990 U.S.	2000 WORLD	2000 U.S.
DEMAND						
CURRENT USES (CHEMICALS, SOLVENTS)	NA	960	NA	1770	NA	<2610
DEVELOPING APPLICATIONS[1]	NA	110	NA	1040	NA	>2610
TOTAL	4020	1070	9370	2810	17400	5220
SUPPLY						
PRODUCTION (FROM NG AND PETROLEUM)	4020	1060	9370	1810	NA	NA
NET IMPORTS (OR FROM COAL)	0	10	0	1000	NA	NA
TOTAL	4020	1070	9370	2810	NA	NA

(1) FUEL AND FUEL ADDITIVES, SINGLE CELL PROTEINS, ACETIC ACID.

6.4 PRICE PROJECTIONS

Fuel price projections through the year 2000, as derived from the DOE Annual Report to Congress, are shown in Table 14. Product demand prices are those paid by consumers. The NG price projections by DOE assume application of the NGPA as presently written. Any speedup in the schedule of price decontrol, or the decontrol of old gas not provided for under the Act, would undoubtedly raise the forecasted gas prices. Methanol manufacturing costs with NG as the feedstock were assumed to remain the same at current levels, in constant 1980 dollars, with gradually increasing prices due to changes in NG raw material cost.

As indicated in the table, the national average price advantage of CNG and LNG over gasoline (including taxes), which amounted to approximately $0.65 (1981 dollars) per equivalent gallon in 1981, is forecasted to remain relatively constant through the 1980s and then increase significantly as petroleum prices rise rapidly. The prices of CNG and LNG produced from coal are projected to be from 11 to 17 percent higher than CNG and LNG based on NG. Methanol now has a price disadvantage (including taxes) of about $0.53 (1981 dollars) per equivalent gallon. Conversely, the cost of methanol from coal is about 35 to 38 percent lower than methanol produced from NG, primarily because of the predicted lower cost of coal, and the economies of scale resulting

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Table 14. U.S. Energy Prices: History and Projections

SOURCE/FUEL TYPE	U.S. ENERGY PRICES, 1980 DOLLARS[1] 1981	1985	1990	2000
SUPPLY PRICES				
OIL, DOLLARS PER BBL				
DOMESTIC WELLHEAD AVERAGE	29.55	40.44	44.55	NA
IMPORTED AVERAGE	33.99	40.96	45.33	NA
NATURAL GAS, DOLLARS PER MCF				
DOMESTIC WELLHEAD AVERAGE	3.60	5.58	5.76	NA
IMPORTED AVERAGE	4.07	6.65	7.17	NA
COAL, MINEMOUTH, DOLLARS PER TON[2]	26.99	31.70	33.40	NA
DEMAND PRICES, DOLLARS PER EQUIV. GAL[3]				
DISTILLATE[4]	0.67	1.04	1.16	1.91
GASOLINE[5]	1.08	1.51	1.60	2.35[6]
NATURAL GAS[7]	0.42	0.67	0.72	0.79
CNG				
FROM NATURAL GAS[8]	0.65	0.90	0.95	1.02
FROM COAL[9]	-	1.05	1.09	1.15
LNG				
FROM NATURAL GAS[10]	0.69	0.93	0.98	1.05
FROM COAL[9]	-	1.08	1.13	1.17
METHANOL				
FROM NATURAL GAS[11]	1.71	1.93	1.95	2.04
FROM COAL[9]	-	1.20	1.26	1.30

(1) FUEL PRICES FROM DOE'S 1980 ANNUAL REPORT TO CONGRESS (MARCH 1981) CONVERTED TO 1980 DOLLARS, UNLESS OTHERWISE NOTED.
(2) NATIONAL AVERAGE.
(3) ENERGY-EQUIVALENT GASOLINE GALLONS, BASED ON 125,000 BTU (HHV) PER GALLON OF GASOLINE.
(4) EXCLUSIVE OF TAXES OF $0.15/GAL$_E$.
(5) EXCLUSIVE OF TAXES OF $0.15/GAL$_E$.
(6) ESTIMATED FROM DATA IN DOE'S 1980 ANNUAL REPORT TO CONGRESS (MARCH 1981).
(7) COMMERCIAL PRICES.
(8) PRICE IS SUM OF COMMERCIAL NG PRICE AND AGA COMPRESSION COST ESTIMATE OF $0.23/GAL$_E$.
(9) PRICES BASED UPON DOE-PROJECTED COAL PRICES AND GENERIC GAS COST EQUATION FOR UTILITY (CNG AND LNG) OR PRIVATE INVESTOR (METHANOL) FINANCING DERIVED BY NATIONAL GAS SURVEY OF THE FEDERAL POWER COMMISSION. COMPRESSION OR LIQUEFACTION COSTS FROM AGA ESTIMATES. PRICES DO NOT INCLUDE DISTRIBUTION MARKUP.
(10) PRICE IS SUM OF COMMERCIAL NG PRICE AND AGA LIQUEFACTION COST ESTIMATE OF $0.26/GAL$_E$.
(11) PRICE BASED ON RAW MATERIAL NG PRICE.

from coal conversion plants that may be an order of magnitude larger than the largest current methanol-from-NG plant. This would result in a price advantage over gasoline in 1985 of about $0.51 (1981 dollars) per equivalent gallon. Although these price trends are generally substantiated by other forecasters, it should be noted that no large coal conversion plants have been built in this country as yet; thus these projected prices remain to be confirmed.

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7. VEHICLE SAFETY

Three areas of potential safety concern have been identified for NG and methanol: (1) environmental and health effects of fuel exposure, (2) fuel system hazards in normal vehicle operation, and (3) hazards under accident conditions. No fundamental problems were found which would preclude the safe use of NG in highway vehicles. However, the available test data on NG vehicles are too limited to be conclusive and further testing should be performed. In general, NG either substitutes new concerns in single-fuel systems, or adds a second set of potential hazards in dual-fuel systems.

7.1 ENVIRONMENTAL AND HEALTH EFFECTS

Assessments of health risks are based on the toxicity of NG and methanol resulting from exposure by inhalation, ingestion, or skin contact. Impacts on the physical environment include the effects of accidental fuel release on terrestrial and aquatic organisms.

In general, NG has significantly less adverse environmental and health impacts than conventional fuels or methanol. Methane in sufficient quantities acts as a simple asphyxiant by displacing air, but is otherwise nontoxic. It is not photochemically reactive, and it has no known adverse environmental impacts. The only known danger is skin damage due to contact with LNG or with cold LNG fueling equipment.

The public and occupational health risks associated with methanol are considered to be equivalent to or less than the risks associated with conventional fuels. Also, the impact of methanol spills and leaks on aquatic and terrestrial environments should be less than with gasoline and diesel fuel, because methanol is water soluble and biodegradable.

7.2 FUEL SYSTEM HAZARDS IN NORMAL OPERATION

The major potential safety concerns associated with NG-fueled vehicles under normal operating conditions are fuel leakage, venting of

LNG boiloff vapor from pressure-relief devices, and corrosive failure of CNG cylinders. Leakage and boiloff of NG would create obvious fire and explosion hazards. However, the hazards associated with NG leakage and LNG boiloff appear to be controllable with existing technologies and established procedures. These include inspection and maintenance procedures that can be readily implemented by fleet operators, and a number of other techniques such as isolation of fuel system components, venting of passenger compartment and fuel storage space, and use of gas-sensing devices or odorants. No new leakage control measures are required for methanol compared with gasoline.

Tank corrosion represents an additional and as-yet-unresolved concern with CNG vehicles. In the past, corrosive NG constituents, such as hydrogen sulfide (H_2S), have caused catastrophic failures of a number of steel cylinders used to transport and store NG, as reported by Italian authorities and by the United States Department of Transportation (DOT). To date, the acceptable maximum concentration ranges of H_2S and other contaminants in NG have not been determined, and the long-term effects of H_2S exposure on high-pressure CNG cylinders are unresolved. However, an excellent safety record has been established by the approximately 275,000 vehicles, mainly private, which currently operate on CNG in Italy. In contrast to the United States, the Italian government administers a comprehensive program involving approval of each CNG conversion, annual inspection of vehicles, periodic testing of fuel system components, control of station siting and design specifications, and stringent gas purity requirements. In addition, aluminum cylinders, or composite cylinders with aluminum inner shells, may well be immune to this problem.

7.3 FUEL SYSTEM HAZARDS UNDER ACCIDENT CONDITIONS

Fuel system hazards under accident conditions are categorized as (1) fuel release upon impact, (2) fuel tank rupture in a fire, and (3) intrusion of fuel system components into the passenger compartment.

Fuel release upon impact can result from fuel tank puncture or crushing, or from damage to other fuel system components. For methanol

and conventional fuels, fuel system integrity is addressed by Federal Motor Vehicle Safety Standard 301, which limits fuel spillage to a specified amount during and after a series of vehicle crash tests. These tests include a fixed frontal barrier crash, rear and lateral moving barrier crashes, and a static rollover test. No corresponding specification has been established for NG. While high-pressure gas cylinders designed to current DOT standards are quite rugged, lightweight CNG tanks manufactured from filament reinforced materials, and considered for introduction in the near term, are potentially more susceptible to impact damage.

A test program conducted in 1971 by DOT included barrier crash tests of CNG dual-fuel vehicles, drop tests of steel CNG cylinders, and sled tests of CNG and LNG cylinder restraining systems. With the exception of one vehicle test, the systems tested were judged to be relatively safe, although specific minor system improvements were recommended by DOT. However, the vehicles, fuel systems, and test conditions employed were not representative of present-day designs and practices. Consequently, the fuel containment and cylinder retention capabilities of current NG conversion equipment are not well established.

Prevention of NG tank rupture in a fire may be achieved by controlled fuel release via pressure relief devices, or by simply designing the fuel tank to have sufficient strength. The first approach is embodied in the DOT regulations for cylinders used for the transport of NG, which do not govern vehicle fuel systems. In contrast, the Italian authorities responsible for CNG vehicles are opposed to the use of pressure relief devices. More data are needed to resolve this issue.

In frontal impacts, fuel tanks mounted in the trunk or cargo compartment can potentially intrude into the passenger compartment as a result of failure of the cylinder retention system or mounting hardware. In addition, intrusion can occur in a rear impact if crush distance is insufficient. Crush distance is of particular concern with contemporary, downsized vehicles converted to NG. It should be noted that aftermarket conversions are not subject to DOT crash standards. Underbody fuel tank

mounting, which has been used in at least one experimental CNG vehicle, lessens the intrusion hazard.

8. USER ECONOMICS

Recent studies of CNG user economics reach diverse conclusions as a direct consequence of marked differences in financial and engineering assumptions used. In addition, economic methodologies vary, ranging from simple payback period calculations to discounted present-value assessments and analyses of return on investment or equity.

Results from recent CNG studies show returns on equity ranging from 9.2 percent before tax, to 130 percent after tax. Simplified calculations indicate that payback occurs in the first year at the earliest, and in 3.7 years at the latest. No similar information was found in the literature for vehicular LNG systems.

The observed wide diversity in key economic analysis assumptions and the attendant variation of economic assessment results stem from the individuality of each NG application. In addition to fuel price, variations in a number of site-related variables have a significant impact on economic feasibility. These variables include (1) the proximity of the fueling station site to suitable electrical power and distributed NG supply, (2) the need for electrical transformers, concrete slabs, walls, fencing, shelter, and driveways, and (3) the cost of building permits, and applicable sales and property taxes. Other parameters impacting economic feasibility include the energy equivalency factor between NG and gasoline, vehicle fleet size, annual mileage driven, selected compressor flow capacity, compressor cost, and financing costs.

Because of the large number of factors and their wide variation, a generalized parametric analysis was performed as part of this study to identify the sensitivity of an economic figure of merit to changes in key system parameters. This was accomplished by using before-

tax payback period as the figure of merit, with all future fuel cost savings discounted to their present value. The fueling station investment cost is based on the required compressor capacity and on recent data relating compressor capacity to total station investment.

Analysis results are presented in Figure 4 for different vehicle fleet sizes in terms of discounted before-tax payback period versus fueling station cost. The system parameters held constant in these

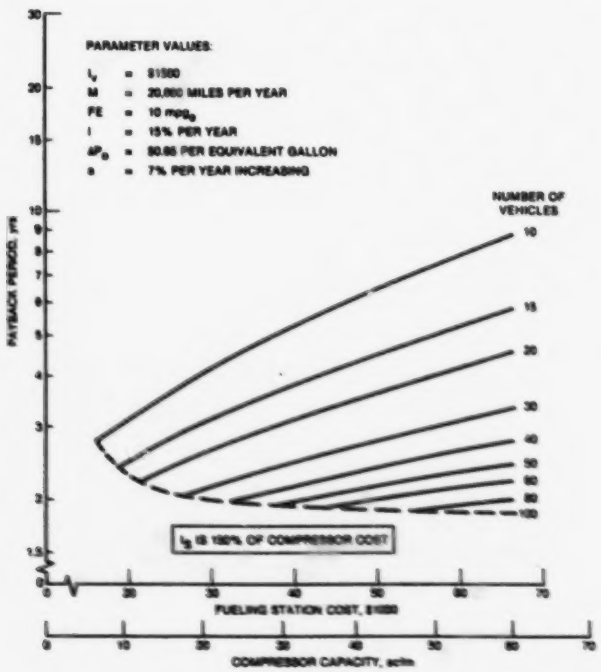

Figure 4. Before-Tax Payback Period for CNG Vehicle Fleets

calculations are (1) a per vehicle conversion cost, I_v, of $1500, (2) a per vehicle annual distance driven, M, of 20,000 miles, (3) a fleet average energy-equivalent fuel economy, FE, of 10 mpg_e for CNG and gasoline, (4) an annual interest rate, i, of 15 percent per year, (5) an initial CNG price advantage relative to gasoline, ΔP_o, of $0.65 per equivalent gallon,

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(6) an annual increase in the CNG price advantage, a, of 7 percent, and (7) a fueling station investment cost, I_S, of 150 percent of compressor cost.

The dashed line in Figure 4 defines payback periods for optimally sized fueling stations. In these cases, compressor capacity is fully utilized to accommodate vehicle operation entirely on CNG. Non-optimal payback periods occur when the fueling station is oversized, or when gasoline is used in place of CNG for a portion of fleet operations. As detailed in Volume II, discounted before-tax payback periods for a 100-vehicle fleet, using optimally sized fueling stations, vary from about 0.9 to 3.9 years, as individual system parameters are varied over a typical range of values. The optimal payback period for a 10-vehicle fleet varies from about 1.1 to 4.7 years. Reduction in vehicle conversion cost from the $1500 to $2000 range used in the parametric analysis to the current best estimate of $1250 to $1850 results in a small reduction in payback period. Additional moderate reductions may be realized through fuel economy improvements, which are achievable with CNG by means of engine spark advance and air-fuel mixture ratio optimization.

For the cases examined in this study, the initial price advantage of CNG over gasoline is the most important parameter affecting optimal payback period. For a 100-vehicle fleet, the payback period increases about 1.5 percent for each 1 percent decrease in price advantage, while a 10-vehicle fleet exhibits a 1.6 percent sensitivity. For the 100-vehicle fleet, vehicle conversion cost is the second most important parameter, with a payback period sensitivity of about 0.7 percent. The fueling station investment requirement is the second most important parameter for a 10-vehicle fleet, showing a sensitivity of about 0.6 percent. Other payback period sensitivities range from about 0.1 to 0.5 percent.

In general, these results show that the use of CNG as a vehicle fuel is likely to be economically attractive for many automotive applications, particularly for large fleets. However, wide application-

to-application variations and uncertainties in key parameters preclude definitive general conclusion. Each application must be analyzed individually.

Results from an economic analysis of LNG systems show discounted before-tax payback periods for a 100-vehicle fleet ranging from 0.5 to 3.9 years, which is comparable to optimized CNG systems. These results are based on the purchase of commercially available LNG trucked to the fleet fueling station, and on preliminary station cost data provided by one source.

Methanol user economics were also briefly analyzed. Currently, methanol costs more than gasoline on an energy basis, even considering potential improvements in engine efficiency, and its use is not economically attractive. However, if the projected low price of methanol provided from coal becomes a reality, conversion to methanol operation would provide attractive before-tax payback periods of 1 to 2 years. This is based on conversion of existing fueling stations to methanol dispensing, with no user investment for station conversion.

9. RESEARCH NEEDS

The assessment of issues on the use of methane-related fuels in fleet automobiles, trucks, and buses indicates that industry has made significant progress towards implementing NG as a vehicle fuel. However, additional research is needed in the following areas to enhance implementation of NG in the automotive sector. Three program categories have been identified: (1) performance, fuel economy, and emissions of NG-fueled vehicles, (2) vehicle safety, and (3) studies and assessments. These needs are highlighted in the following subsections.

9.1 PERFORMANCE, FUEL ECONOMY, AND EMISSIONS OF NG-FUELED VEHICLES

This research category consists of five programs, which are designed to provide the basic technical information required to achieve full implementation of NG for automotive vehicles.

- ESTABLISHMENT OF A STEADY-STATE AND DRIVING CYCLE TEST DATA BASE, USING LATE-MODEL SI AUTOMOBILES AND TRUCKS CONVERTED TO DUAL-FUEL OPERATION

  There is a lack of conclusive performance, fuel economy, and emissions data for vehicles tested sequentially on NG and gasoline. These data are needed to establish fuel economy, performance, and emissions characteristics of late-model vehicles operated on NG.

- DETERMINATION OF THE EFFECTS OF ENGINE RETUNING ON FUEL ECONOMY, EMISSIONS, AND PERFORMANCE OF LATE-MODEL AUTOMOBILES AND TRUCKS OPERATED WITH NG

  The definition of optimal engine calibrations for NG in current and future vehicles requires multicylinder engine tests. Parameters to be evaluated include spark timing, spark intensity, air-fuel ratio, exhaust gas recirculation rate, and gas induction temperature.

- ESTABLISHMENT OF DESIGN CRITERIA FOR AN OPTIMIZED SINGLE-FUEL NG VEHICLE

  Coordinated research is needed to determine the benefits of optimizing SI engines to operate solely on NG. Modifications such as increased compression ratio, altered valve timing, and turbocharging are expected to significantly increase engine power and reduce fuel consumption.

- INVESTIGATION OF NG APPLICATION IN AUTOMOTIVE DIESEL ENGINES

  The growing usage of diesel engines in cars and trucks gives impetus to research on NG application to these engines. In particular, practical retrofit techniques should be investigated to allow significant near-term benefits in diesel truck fleets.

- INVESTIGATION OF UNCONVENTIONAL NG CONTAINMENT SYSTEMS

  Improvement in properties of adsorptive materials, such as activated carbon, molecular sieves (zeolites), and silica gels, could result in vehicular NG storage systems competitive

with LNG systems. In addition, small systems for capturing NG vented from vehicular or fueling station LNG tanks should be investigated.

9.2 VEHICLE SAFETY

Three research programs have been identified to resolve concerns for NG vehicle safety. One program involves tests of fuel system behavior under accident conditions, particularly vehicle impact and fire, and one program is concerned with cylinder corrosion. Research supporting establishment of NG vehicle codes and standards comprises the third program.

- o EVALUATION OF NG SYSTEM CRASHWORTHINESS AND FIRE SAFETY

  Limited NG vehicle impact tests performed more than a decade ago may not apply to current and future systems. Crash tests of contemporary vehicles and several state-of-the-art NG systems are needed to establish crashworthiness. Also needed are tests to determine CNG and LNG tank rupture and pressure relief characteristics. CNG tests should include steel and composite cylinders both with and without pressure relief devices. LNG tests should include several tank shapes, materials, and inner tank support designs.

- o INVESTIGATION OF CNG CYLINDER CORROSION

  Investigation of corrosion resistance of CNG cylinders exposed to NG contaminants is needed. Allowable contaminant levels, particularly H_2S and moisture, should be determined for current and proposed cylinder designs and materials.

- o DEFINITION OF NG FUEL SYSTEM STANDARDS

  Definition of standards is needed to ensure proper design, manufacture, performance, installation, and inspection of NG fuel systems. No nationally recognized codes or regulations for NG systems exist, but the AGA is currently active in this area.

9.3 STUDIES AND ASSESSMENTS

The following three programs examine potential barriers to expanded NG implementation in the transportation sector, and compare petroleum savings to alternative uses of NG.

- ASSESSMENT OF INSTITUTIONAL BARRIERS TO NG USE IN AUTOMOTIVE VEHICLES

  Existing or potential institutional barriers to NG utilization in the transportation sector need to be identified in such areas as safety, emissions, and NG storage.

- COMPARISON OF NG BENEFITS IN FLEET VEHICLES VERSUS STATIONARY SYSTEMS

  The overall resource utilization efficiency and petroleum displacement potential of NG in fleet vehicles should be compared to stationary applications, such as industrial engines and power plants.

- COMPARISON OF NG BENEFITS IN FLEET VEHICLES VERSUS CONVERSION TO ELECTRIC VEHICLES

  The potential petroleum savings resulting from the use of NG in fleet vehicles should be compared to the savings available by use of electric vehicles. The fuel consumption comparison should account for the weight effects of necessary vehicle modifications.

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GLOSSARY

AGA	American Gas Association
BBL	barrels
BETC	Bartlesville Energy Technology Center
bhp	brake horsepower
Btu	British thermal unit
CNG	compressed natural gas
CO	carbon monoxide
DOE	Department of Energy
DOT	Department of Transportation
EPA	Environmental Protection Agency
gal_e	energy-equivalent (gasoline or diesel fuel) gallon
GPY	gallons per year
HC	hydrocarbons
HHV	higher heating value
H_2S	hydrogen sulfide
LDV	light-duty vehicle
LNG	liquefied natural gas
Mcf	thousands of cubic feet
MD	medium duty
mpg_e	miles per energy-equivalent (gasoline or diesel fuel) gallon
mph	miles per hour
MSW	municipal solid waste
NG	natural gas
NGL	natural gas liquids
NGPA	Natural Gas Policy Act
NO_x	oxides of nitrogen
psig	pounds per square inch, gauge
scf	standard cubic feet
scfm	standard cubic feet per minute
SI	spark ignition
SNG	synthetic (or substitute) natural gas
TCF	trillions of cubic feet

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